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Research Article

Correlation Research of TBM Tunnel Rock Mechanical Characteristics, Chiseling Specific Energy, and Abrasion Performance: Case Study of Jiaozhou Bay Subsea Tunnel in Qingdao

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This paper takes Qingdao Jiaozhou Bay subsea tunnel project as the research object to study the relationship among rock mechanical parameters and chiseling specific energy and abrasion performance. SPSS22 was used to analyze the correlation between the parameters. The results show that except for the low correlation with Poisson ratio, all the other parameters in the single factor correlation analysis have high *R*. By taking the chiseling specific energy and abrasion performance as dependent variables, taking each mechanical parameter as an independent variable, multifactor regression analysis and stepwise multifactor fitting were carried out; it was concluded that the abrasion performance was highly correlated with uniaxial compressive strength and integrity coefficient, and the chiseling specific energy is highly correlated with uniaxial compressive strength and softening coefficient. In the process of verifying the fitting models, it is found that, under the influence of quartz vein and microfissure in the specimens, the chiseling specific energy formula has a higher fitting value, while the fitting formula of abrasion performance has a higher reference value for the specimens in the study area.

1. Introduction

In recent years, the whole-section tunnel boring machine (TBM) with its relatively simpler construction organization, quicker tunneling speed, labor-saving characteristic, and only one disturbance to the surrounding rock in the construction process is widely applied in railway tunnel engineering construction [1, 2]. However, this method still has deficiency, such as high tool wear rate, high driving cost, and surrounding rock deformation which can easily lead to stuck drilling.

In previous studies, as discussed by Qi et al. [3] and Acaroglu et al. [4], they tested on the cutting process of different TBM blades; the tool ordering and the specific energy required by TBM are verified and predicted by fuzzy comprehensive evaluation and ideal similarity ordering technique. Or as discussed by Bilgin [5], Sun et al. [6, 7], and Gong et al. [8–12], they based on different geological conditions of tunnel projects, analyzing the impact on different types of tunneling machine drivage efficiency. But in the actual tunnel construction process, as discussed by Xu et al. [13–15], there are a large number of original fractures that intersect with the tunnel axis at different angles. Therefore, as discussed by Wang and Wu [16], Luo [17], Wang and San [18], Xu [19], and Yang [20] [21–28], local geological conditions and various mechanical parameters need to be considered at the same time. Correlation analysis between abrasion performance and its mechanical parameters is carried out by using regression analysis method.

Based on the previous studies, the existing studies mainly focus on the commissioning and prediction of TBM blade size, cutting angle, and other equipment in the construction process as well as the relevant numerical simulation, but there are few studies on the correlation between mechanical parameters, chiseling specific energy, and abrasion performance.

Accordingly, tunnel rock mechanical properties with the degree of tool wear are directly related. Based on the project of Jiaozhou Bay subsea tunnel in Qingdao, this paper studies the correlation between rock mechanical parameters and chiseling specific energy and abrasion performance and establishes the corresponding model to estimate the tool wear and energy loss, so as to save construction time and cost in the construction process.

The Jiaozhou Bay subsea tunnel is located between Tuan Island and Xuejia Island of Shandong Peninsula. The length of the main tunnel is about 6170 m, with a total length of about 3950 m across the sea.

The intrusive rocks are well developed in the area around Jiaozhou Bay. Rock types are exposed from ultrabasic to acidic; the forming time is from Mesoproterozoic to Cenozoic. Among them, the Neoproterozoic Jingningian period, Sinian period, and Late Mesozoic Yanshanian intermediate-acid intrusive rocks are the most developed (Figure 1).

This region is located at the boundary of the North China fault block and the Yangtze fault block; it belongs to the edge of Jiaonan weak uplift. The most obvious geological structure of the tunnel site is the Mesozoic and Cenozoic brittle faults. Regional geological map shows (Figure 2) that the Chaolian Island fault (④) passes through the bay mouth and intersects with the tunnel line at a large angle. And the tunnel site is sandwiched between the Cangkou fault (①) and Pishikou fault (②), and there must be components or secondary faults of the above regional faults at the tunnel site. In the sea area, there are two NE trend faults (Figure 2, 1 and 3) and two NW trend faults (Figure 2, 4 and 5) that intersect with the tunnel; the first two faults can be regarded as the components of the Pishikou fault (②), while the last two NW trend faults may be the components of the South Chaolian Island fault (④) (Figure 2).

2. Materials and Methods

2.1. Parameter Determination. Three different section granites within the tunnel excavation interval are selected in this paper. After determining the chiseling specific energy (Equation (1)) and the abrasion performance, the uniaxial compressive test (Tables 1 and 2) of the rock was carried out by the MT150 press machine and the automatic function recorder.

$$a = \frac{A}{V} = \frac{N * A_0}{(\pi/4) * D^2 * H}, \quad (1)$$

where a is the chiseling specific energy (J/cm^3), A is the total impact energy (J), V is the rock volume (cm^3), N is the shock number, A_0 is the single impact energy (J), D is the actual hole diameter (cm), and H is the hole depth (cm).

Figure 1: Borehole lithologic photograph.

2.2. Correlation Analysis of Parameters. Based on the experimental data, firstly, the influence of various mechanical parameters of granite on chiseling specific energy (a) and abrasion performance (b) and internal correlation are analyzed by SPSS22 (Statistical Package for the Social Sciences 22) single-factor condition.

a and b are taken as dependent variables; E_s, σ_c, μ, K_V, K_P, and V_P were selected for fitting.

The SPSS determines the correlation between variables based on F test and T test; it is expressed as the correlation coefficient R (sig < 0.05) (Equation (2)); the partition of the coefficient is as follows: no correlation ($|R|$ <0.3), low correlation (0.3 < $|R|$ <0.5), significant correlation (0.5 < $|R|$ <0.8), and high correlation (0.8 < $|R|$).

$$R = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - \bar{X}}{S_X}\right)\left(\frac{Y_i - \bar{Y}}{S_Y}\right). \quad (2)$$

2.3. Correlation Analysis of Chiseling Specific Energy and Mechanical Parameters. The fitting results of a and mechanical parameters obtained by using the quadratic term model (Figure 3 and Table 3) have the greatest correlation: R of σ_c under the condition of using quadratic term model is 0.991, which is the highest. R of V_P is 0.970, R of E_s is 0.947, R of K_P is 0.959, and R of K_V is 0.978 with sig < 0.05. It indicates that there is a certain correlation between a and the above mechanical parameters, among which the correlation with E_s is the lowest. In the fitting with μ, its sig is greater than 0.05, indicating that the correlation between them is weak.

2.4. Correlation Analysis of Abrasion Performance and Mechanical Parameters. The curve fitting results between b and mechanical parameters are obtained by using the same algorithm (Figure 4 and Table 4). As can be seen from the fitting results, b has a good correlation with σ_c under the condition of using the S model (R = 0.993); under the condition of using the quadratic term model, the relation between V_P, E_s, K_P, and K_V is better, and R is 0.986, 0.966, and 0.987, respectively. It indicates that there is also a high correlation between

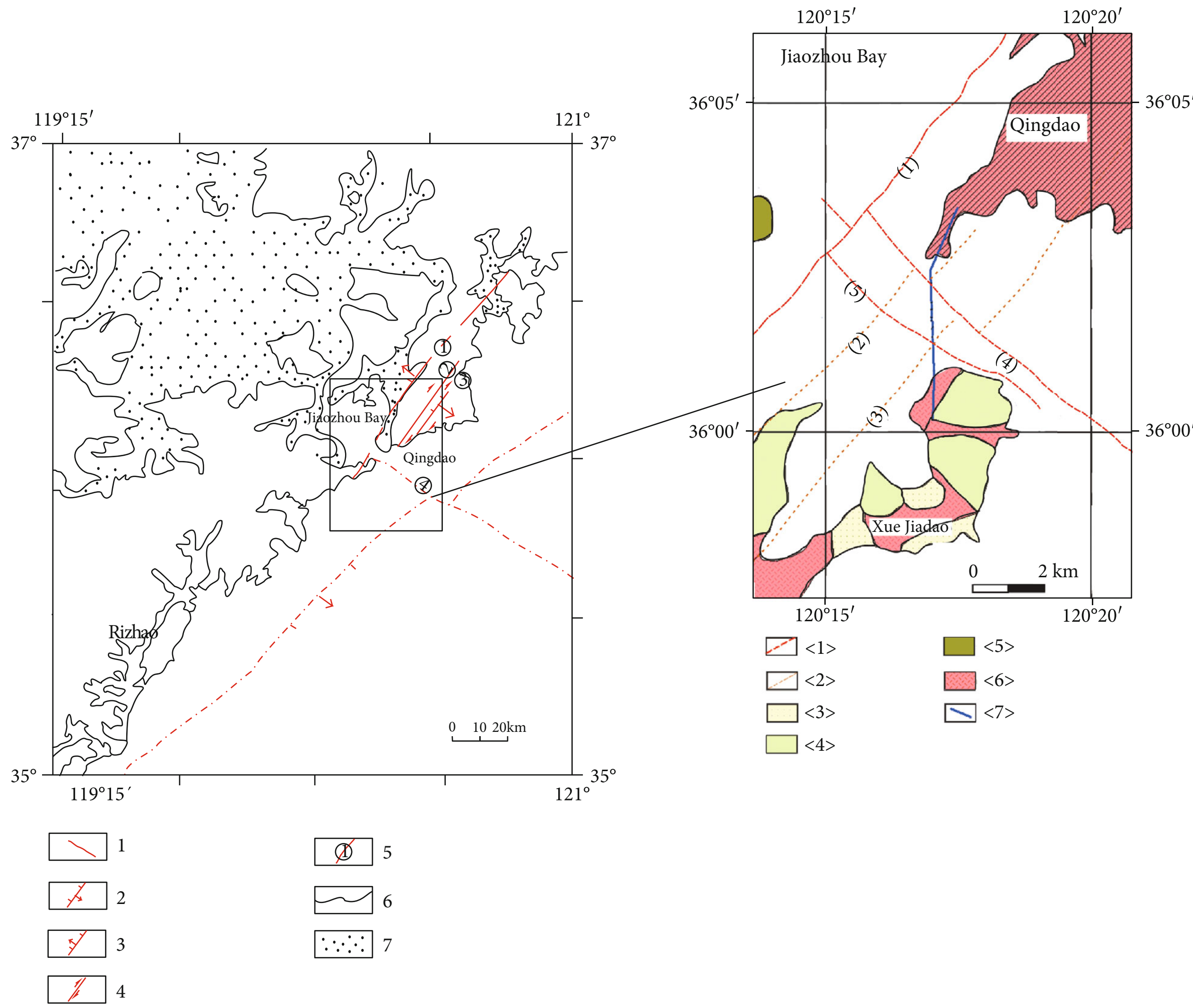

Figure 2: Regional geological map. 1: buried fault; 2: thrust fault; 3: normal fault; 4: strike-slip fault; 5: main fault number; 6: geological boundary; 7: Quaternary. Fault: ① Cangkou fault, ② Pishikou fault, ③ Wangjiage fault, ④ South Chaolian Island fault. <1>: early-middle Pleistocene buried faults; <2>: pre-Quaternary buried faults; <3>: Quaternary; <4>: Mesozoic; <5>: Proterozoic; <6>: Mesozoic intrusions (medium acid); <7>: the tunnel route. Fault: (1) Cangkou fault, (2) Xin Island fault, (3) Licang District Government-Huiquanjiao fault, (4) South Tuan Island fault, (5) North Xuejia Island fault.

Table 1: Table of test results of granite specific energy of chiseling.

Lithology	Sampling range	Number of samples	Impact hammer weight (kg)	High impact hammer falls (m)	A_0 (J)	N	A (J)	D (cm)	H (cm)	a (J/cm^3)
	ZK3+306.17	10		1	1.5	400	600	3.8	1.23	43.1
Granite	ZK3+135.87	10	4	1	1.5	400	600	3.8	1.1	47.9
	ZK2+716.52	10		1	1.5	400	600	3.8	1.19	44.5

Table 2: Granite mechanical test data.

Sampling range	Lithology	Number of samples	Uniaxial compressive strength σ_c (MPa)	Longitudinal wave speed V_P (m/s)	Softening coefficient K_P	Elastic modulus E_s (GPa)	Poisson ratio μ	Integrity coefficient K_v	Abrasion performance b (1/10 mm)
ZK3+306.1		15	122.3	5070	0.762	49.51	0.135	0.66	5.18
ZK3+135.87	Granite	15	123.6	5028	0.763	56.8	0.142	0.87	5.14
ZK2+716.52		15	127.9	4981	0.76	58.5	0.197	0.86	5.01

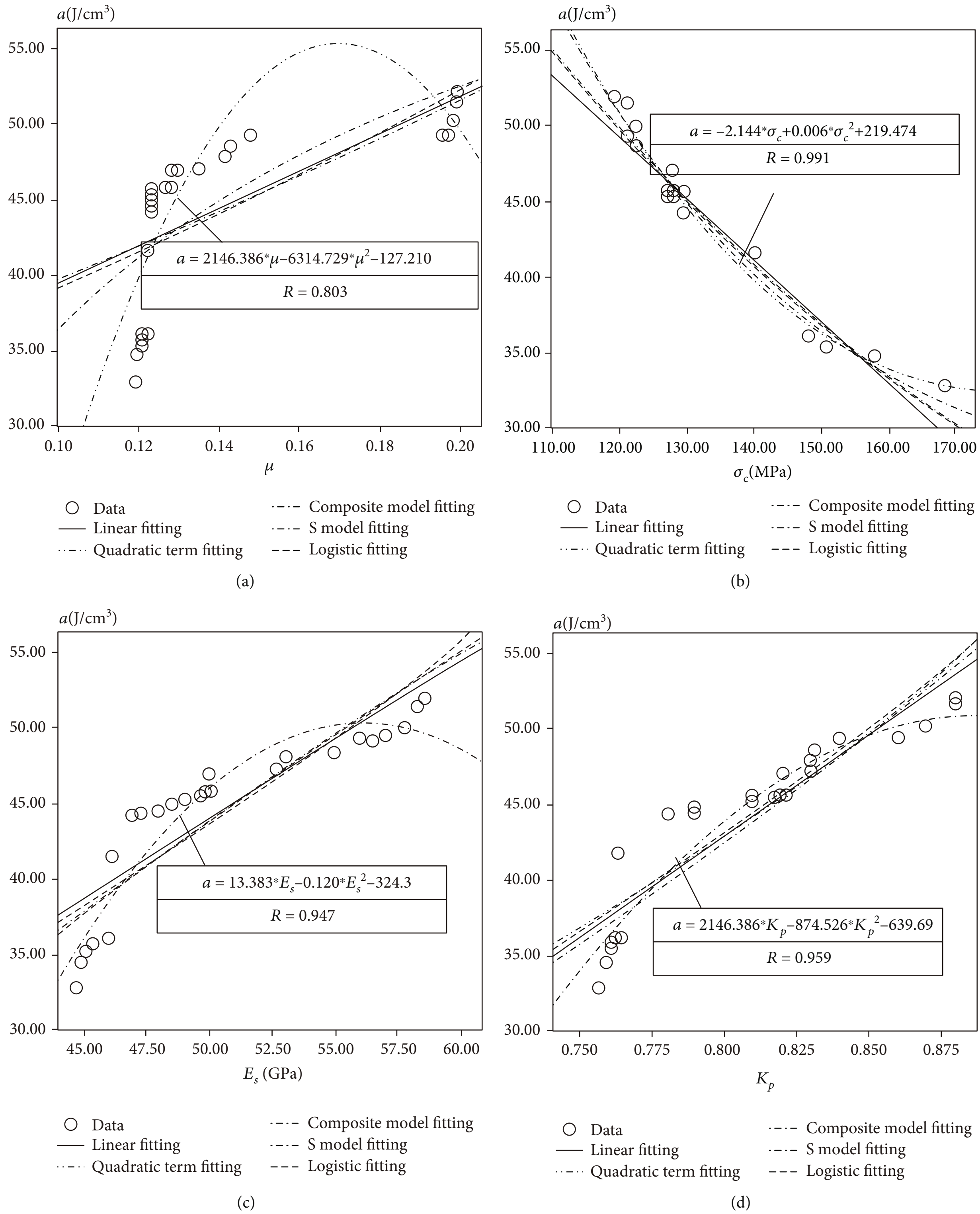

Figure 3: Continued.

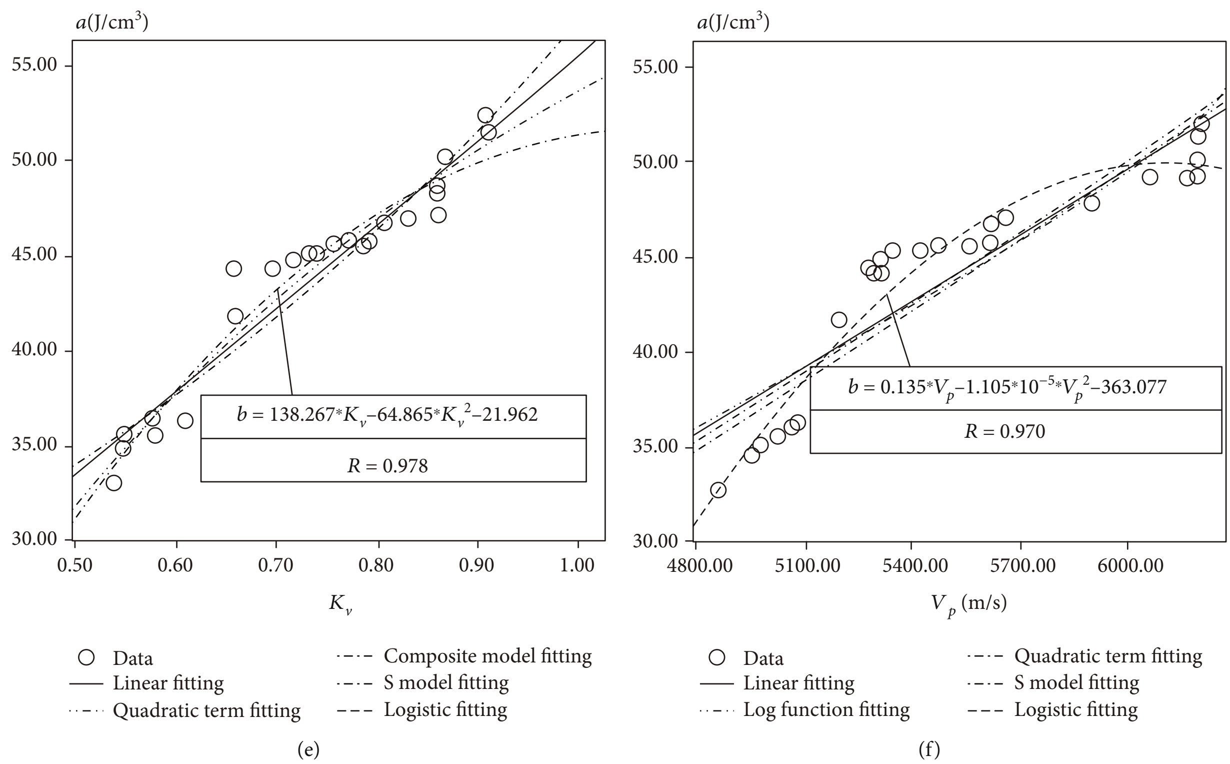

Figure 3: Chiseling specific energy and mechanical parameter diagram.

Table 3: Results of granite physical mechanical parameters and chiseling specific energy fitting.

	a (J/cm^3)	R
μ	$a = 2146.386\mu - 6314.729\mu^2 - 127.210$	0.803
σ_c (MPa)	$a = -2.144\sigma_c + 0.006{\sigma_c}^2 - 219.474$	0.991
E_s (GPa)	$a = 13.383E_s - 0.120{E_s}^2 - 324.3$	0.947
K_P	$a = 1554.238K_P - 64.865{K_P}^2 - 639.69$	0.959
K_V	$a = 138.26K_V - 64.865{K_V}^2 - 21.962$	0.978
V_P (m/s)	$a = 0.135V_P + 1.105 * 10^{-5}{V_P}^2 - 363.077$	0.970

b and the above mechanical parameters, among which the correlation with E_s is the lowest. In the fitting with μ, $R\,(0.776) < 0.9$, indicating a weak correlation between them.

To sum up, it can be seen from the fitting results under two dependent variable conditions that b has a higher correlation than a; the reason may be that the rock strength characteristics have a more direct impact on b, while a requires a more comprehensive analysis considering the anisotropy of rock; the correlations between the two dependent variable conditions and μ are weak.

3. Results and Discussion

In order to explore whether the rock mechanical parameters have a more comprehensive influence on a and b, based on multidependent variables, stepwise analysis was carried out.

3.1. Multifactor Regression Analysis Result. On the premise of taking a and b as dependent variables, the stepwise multifactor fitting shows that, from the fitting of$a$,σ_c, and$K_P$under the comprehensive influence of model, the highest correlation was 0.991 (sig < 0.05) (Equation (3), Table 5). From the fitting of b (Equation (4), Table 6), chosen σ_c and K_V, the maximum correlation is 0.996 (sig < 0.05).

$$a = 40.412 - 0.281 * \sigma_c + 50.758 * K_P, \tag{3}$$

$$b = 6.277 - 0.014 * \sigma_c + 0.738 * K_V. \tag{4}$$

To sum up, in multifactor fitting, a is comprehensively affected by σ_c and K_P, while b is comprehensively affected by σ_c and $K_V = (V^1{}_P/V_P)^2$ ($V^1{}_P$: V_P of rock mass; V_P: V_P of rock), which are mainly controlled by rock strength and the development of internal structural plane and fracture in rock mass. And $K_P = (\sigma^1{}_c + \sigma^2{}_c)$ ($\sigma^1{}_c$: σ_c in saturated condition; $\sigma^2{}_c$: σ_c in dry condition). K_P can better reflect the water resistance of rock. Therefore, these three independent variables can reflect the characteristics of rock more comprehensively.

3.2. Model Validation. In order to verify the universality of the two formulas, metamorphic sandstone and granodiorite were randomly selected in the study area, and experiments were conducted under the same conditions. In the practical application, it is found that there is a larger error in the fitting of mechanical parameters with a, while b has a smaller error. Therefore, it can be inferred that the fitting formula of b has a higher preference value for rock in the study area (Table 7).

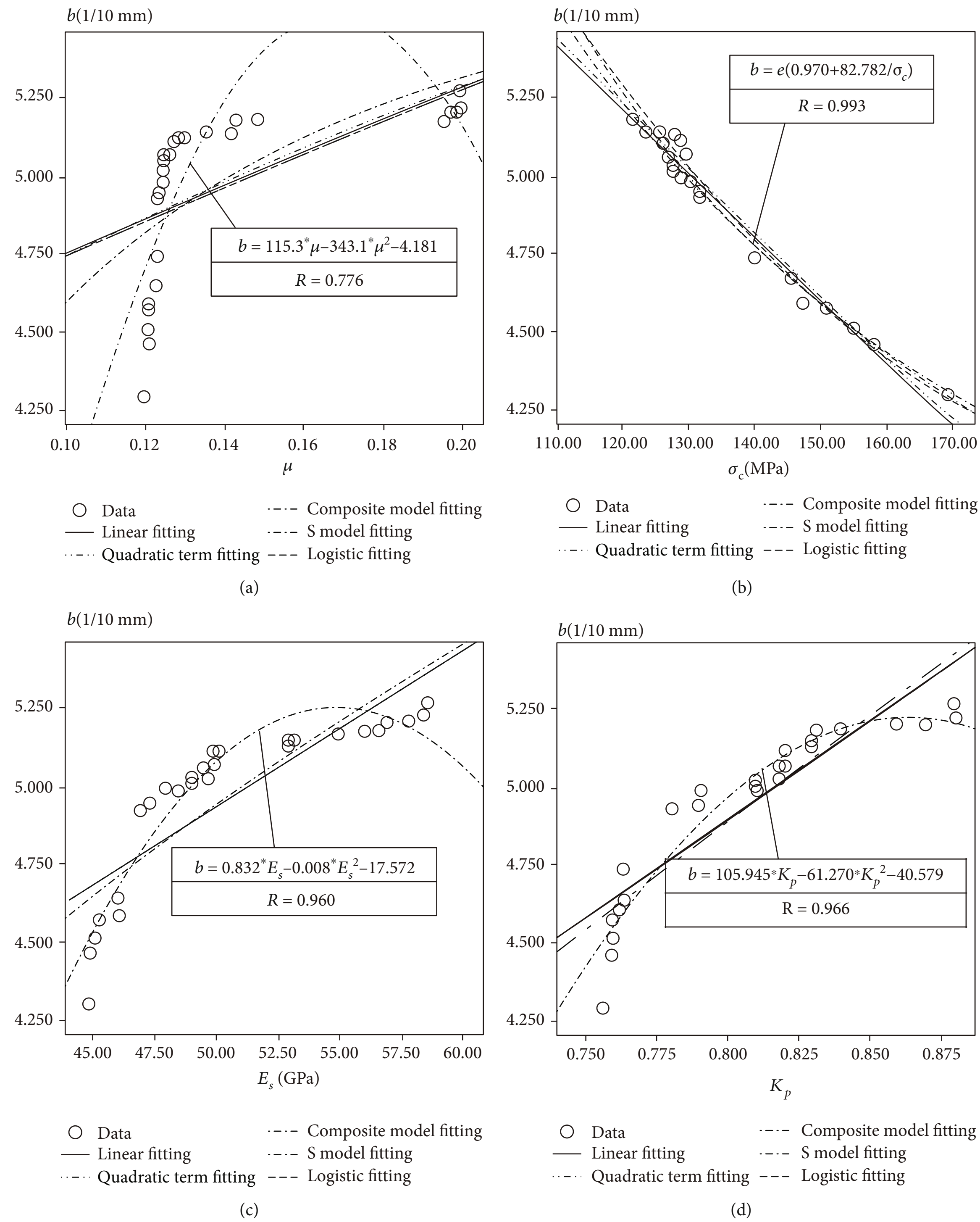

Figure 4: Continued.

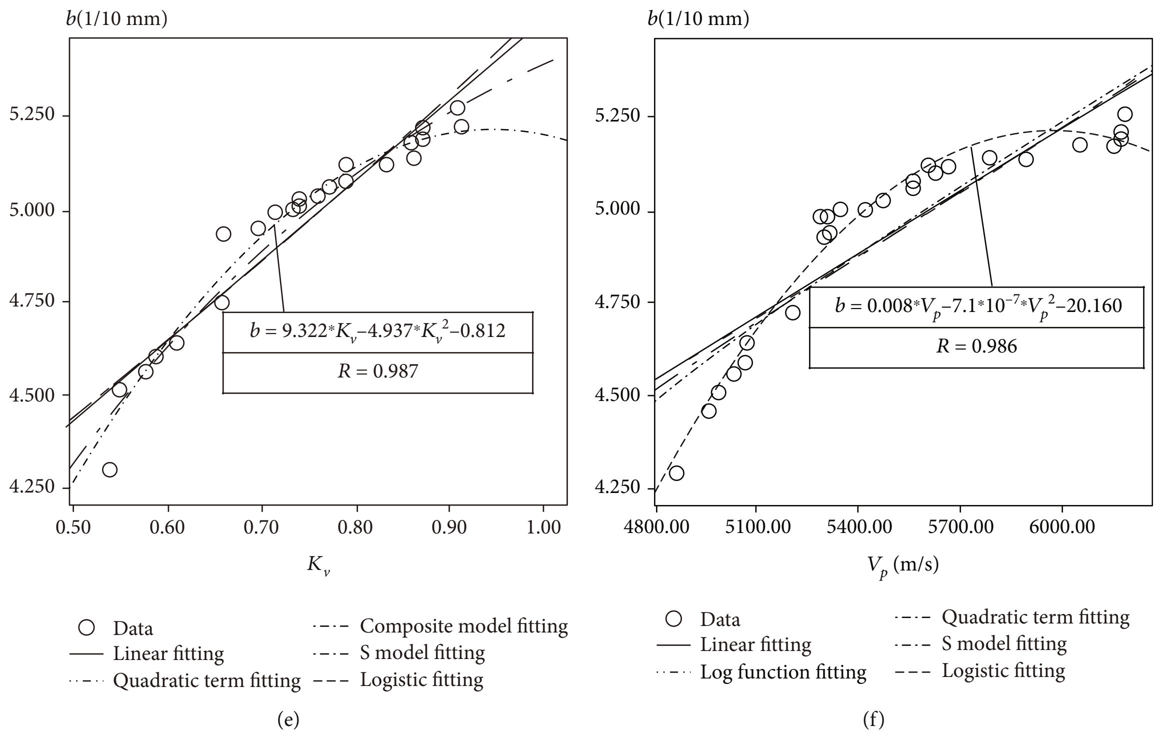

FIGURE 4: Abrasion performance and mechanical parameter diagram.

TABLE 4: Results of granite physical mechanical parameters and abrasion performance fitting.

	b (1/10 mm)	R
μ	$b = 115.3\mu - 343.1\mu^2 - 4.181$	0.776
σ_c (MPa)	$b = e^{(0.970+82.782/\sigma_c)}$	0.993
E_s (GPa)	$b = 0.832E_s - 0.008{E_s}^2 - 17.572$	0.960
K_P	$a = 105.945K_P - 61.270{K_P}^2 - 40.579$	0.966
K_V	$b = 9.322K_V - 4.937{K_V}^2 + 0.812$	0.987
V_P (m/s)	$a = 0.008V_P + 7.1 * 10^{-7}{V_P}^2 - 20.160$	0.986

TABLE 5: The multifactor regression analysis model coefficient of the chiseling specific energy.

Dependent variable: a					
Number	Parameter	B	R	R^2	sig
1	Constant	98.397	0.9741	0.948	0.000
	σ_c	-0.407			0.000
2	Constant	40.412	0.99	0.982	0.000
	σ_c	-0.281			0.000
	K_P	50.758			0.000

The reasons for error are the development of the quartz vein, the drill abrasive on a quartz vein, and the experimental rock microfracture developed, causing the actual σ_c and a to be lower, while still not excluded is the error caused by the sample numbers which is not enough. Therefore, influence factors of the metamorphic sandstone and the magmatic rocks can be further researched.

TABLE 6: The multifactor regression analysis model coefficient of abrasion performance.

Dependent variable: b					
Number	Parameter	B	R	R^2	sig
1	Constant	7.660	0.989	0.977	0.000
	σ_c	-0.020			0.000
2	Constant	6.277	0.996	0.993	0.026
	σ_c	-0.014			0.000
	K_V	0.738			0.000

4. Conclusions

Taking Qingdao Jiaozhou Bay subsea tunnel as the research object, this paper conducts research and analysis on the rock mechanical parameters and a and b, drawing the following conclusions:

(1) In the process of a single factor variable fitting, a and b have a high correlation with mechanical properties: a is negatively correlated with σ_c under the condition of using the quadratic curve model. It positively correlates with V_P, E_s, K_V, and K_P. b is negatively correlated with σ_c under the S model and positively correlated with V_P, E_s, K_V, and K_P under the condition of using the quadratic curve model. But the correlations with μ are low

Table 7: Experimental verification table of chiseling specific energy and abrasion performance.

Lithology	Impact hammer weight (kg)	High impact hammer falls (m)	Observing group					Fitting group	
			σ_c (MPa)	K_V	K_P	b (1/10 mm)	a (J/cm^3)	b (1/10 mm)	a (J/cm^3)
Metasandstone	1.5	1	127	49	0.121	5.059	44.534	5.058	45.617
			130	48.5	0.123	4.984	42.073	4.988	44.987
			140	47	0.195	4.764	40.463	4.737	41.682
			148	50	0.124	4.6148	35.063	4.59	36.132
			148	49.9	0.199	4.6147	34.063	4.64	36.182
Granodiorite			121.3	58.34	0.125	5.216	50.501	5.205	53.7
			122.2	49.56	0.129	5.189	49.409	5.2	53.7
			122.9	53.07	0.120	5.169	48.946	5.18	54
			125.1	56.6	0.124	5.109	48.588	5.11	54.9
			126.8	52.72	0.128	5.064	47.477	5.069	54.9

(2) In the analysis of multifactor linear regression, b shows a strong correlation with σ_c and K_V ($R = 0.996$). a shows a strong correlation with σ_c and K_P ($R = 0.991$), which are mainly affected by rock mass strength and anisotropy and can better represent the mechanical properties

(3) Metamorphic sandstone and granodiorite were selected to verify the fitting models, showing that actual b is very close to that of the fitting group. And the fitting group of a is generally higher; the reason is that the model does not fully reflect the fracture and structural surface development in rock, as well as the differences in mineral chemical composition, which can be further studied

Data Availability

The test data used to support the findings of this study are included within the article. Readers can obtain data supporting the research results from the test data tables in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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